QUENCH PROTECTION AT HERA

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Introduction

The Hadron-Electron-Ring-Accelerator (HERA), now under construction at DESY, Hamburg, consists of a 30 GeV electron storage ring and a storage ring for protons of 820 GeV. The circumference of the machines is 6.336 km. Most of the magnets for the proton ring are superconducting. In total there are 416 horizontally and 6 vertically bending dipoles /1/, 224 quadrupoles /2/ and many correction magnets /3/, all of them superconducting. The magnets are described elsewhere, here the quench protection is discussed.

Superconducting magnet system

The main magnets, both dipoles and quadrupoles, are connected electrically in series. Fig. 1 shows the connection scheme. The return current lead passes outside the cold iron yoke. A current of 5027 A is needed to achieve a central field of 4.682 T in the bending magnets and a central gradient of 91.19 T/m in the quadrupoles for an energy of 820 GeV. Under these conditions, 820 kJ of magnetic energy are stored in each dipole and 333 MJ in the main magnets in total. The design value for the quench protection system was set to accomodate the typical quench current, at 4.6 K, of 6500 A, which means 1.37 MJ stored per dipole or 557 MJ stored in the system. As has been pointed out elsewhere /4,5/, there is no practical way to extract a major fraction of the stored magnetic energy out of a quenching magnet if the magnets are connected in series. At FNAL /6/ groups of magnets, one or more of which might be quenching, can be bypassed with thyristors fired on command of a microprocessor. The energy stored in this group of magnets, has to be absorbed in the quenching magnet(s), while the energy of all other magnets can be dumped into resistors. At BNL /7/, for lower magnet current ramp rates, diodes were chosen as bypass devices. Once a threshold voltage is reached, diodes open automatically and do not require an active firing signal. This makes diodes the optimal choice for storage ring applications but on the other hand, diodes are difficult to use. If the magnet winding contains both a forward and a backward conductor, only one of them can be bypassed.

At HERA all magnets are of the cold iron type, which allows us to place the backward conductor outside the iron, but still at a temperatur of 4.6 K. Outside the coil, the conductors can easily be made sufficiently thick so that no bypass is necessary in the backward conductor. The forward conductor in the dipoles is bypassed with diode pairs with each diode separating one half-coil from the rest of the system. This arrangement reduces the energy to the magnet to 1/(2+2k) of the stored energy, where k is the coupling between the two halfcoils (typically k=.3). The quadrupoles have considerably less energy stored and do not need two diodes.

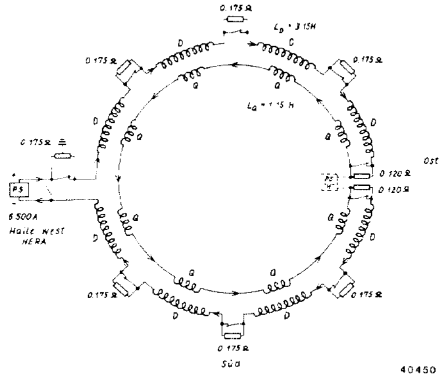

Fig. 1: Electrical Connection of the Main Magnet

In case of a quench, the detection system (to be described later) opens all switches in Fig.1 and the magnitude of the voltages rises (for J = 6500 A) to ± 600 V. The energy, stored in all nonquenching magnets, is dumped into the resistors with a time constant of about 18 s. If however, one of the switches does not open, voltages of 1300 V, and more, can occur, and the time constant will increase. Both effects might cause damage and have to be avoided.

Cold diodes

Diodes are normally not designed to work at a temperature of 4.6 K, but if they somehow start to conduct, they will heat up and eventually reach normal operating temperatures. The contact surfaces have to be cooled to avoid overheating of the semiconductor. In a helium vessel, effective cooling can only be provided by large heat-sinks of sufficient thermal mass. Our early tests were done, as at BNL /7/, with diode wafers obtained from various suppliers. Pieces of flat copper pressed against the contact surfaces of the wafers acted as cooling blocks. These copper blocks also carried the connection to the power-supply. Unfortunately, this simple construction turned out to be unreliable. Sometimes diodes overheated at isolated spots, or the applied contact pressure, and hence, cooling, was not evenly distributed. Discussions with manufacturers revealed additional problems with the rubbing of copper on the aluminized silicon surface.

Fig. 2 shows a photograph of an diode assembly now in use to avoid those problems. The diodes, packed as they come from the manufacturer, are sandwiched between copper blocks. These are pressed together with copper beryllium spring washers. The centricity of the force is guaranteed by locating pins and guidance steel pieces at both ends. G10 endcaps insulate the steel top and steel bottom from the electrical connections. Four insulated steel rods keep the necessary force of 20 kN on the spring washers. The diode assembly for the quadrupole magnets contains only one diode and the two smaller copper pieces.

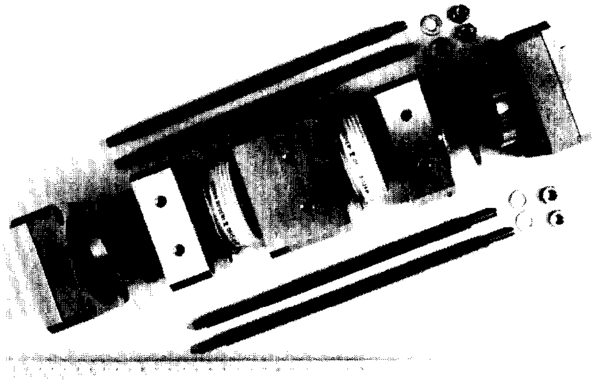

Fig. 2: Dipole Diode Assembly before Clamping

To find suitable diodes, we performed tests on samples from various manufacturers. The specific demands, among others, are a reverse voltage, at T=4K, of more than 250 V, and a forward voltage, at 4 kA, of less than 1.2 V (room temperature). The diodes were exposed, at liquid helium temperature, to an exponentially decaying current pulse of 6500 A peak. Voltages and cooling block temperatures were recorded. These tests were repeated up to 60 times in Helium (480 times in LN_2). Most diodes overheated and melted locally. Others survived, but absorbed more than 200 kJ. From the tested diodes, the following were accepted as cold diodes for HERA: BBC DSA 1508-11A(B), BBC DS 1508-02A01 (modified DS 6000) and Siemens DESY-special.

The diode DS 1508-02A01, a mechanically modified DS 6000, was finally selected because it proved to have the lowest on-resistance and a competitive price. Except for a polyimide varnish, no organic materials are used in these diodes. More than 50 pairs of the production lot have been sucessfully tested with 20 current pulses. One diode showed a reverse voltage at 4 K of 300 V only ($J_r \leq 3$ mA) but within specification. All others are much better.

Lattice displacement damage due to neutron bombardment presents a potential danger for the diodes. It results mainly in three effects , two of them desirable: a decrease of the forward voltage at low currents and an increase of the reverse breakdown voltage, but the dominant effect is an increase of the resistance, resulting in an increase of the energy dissipation at high currents. Tests were carried out at room temperature with 14 MeV neutrons at a local cancer therapy centre /8/. After an irradiation of 10^{12} n/cm^2 (equivalent to some years operation) no changes could be observed. This result compares well with other observations /9/. The heavily doped and thin wafers of the DS 6000 type are an optimal choice with respect to radiation even at low temperatures.

Quench detection system

Independent of the cold diodes, a quench detection system is needed to trigger the opening of the switches (see fig. 1) and, if necessary, to initiate the firing of the heater bands in the magnets.

All superconducting magnets at HERA have a center tap. This allows, as sketched in Fig.3, detection of imbalance of a bridge. If during a quench the resistances of the two half coils develop differently, a current will flow through the middle of the bridge. Common mode signals (during ramping or from noise) are suppressed. Absolutely identical quenches have never been observed, but four magnets are combined to a super bridge, which would detect such anomalies.

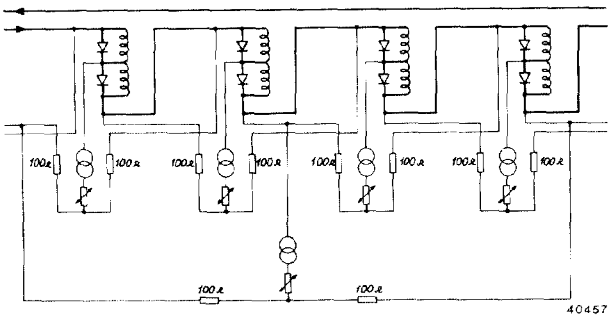

Fig. 3. Quench Detection

The current sensing element has to be close to the magnet. This sensor is a magnetic amplifier. The device decouples the potentials and amplifies a 100 mV signal by a factor of 100 to yield a 10 V signal, on a 1 KΩ resistor, phase-locked to an AC driving source. Magnetic amplifiers are insensitive to radiation. The electronics to detect the 10 V signals can be placed in the experimental halls. Prototype systems have been in use for over a year.

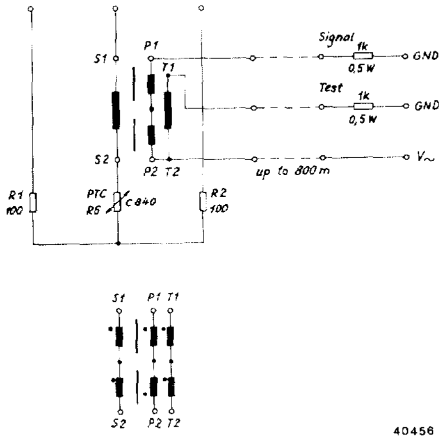

Fig. 4: Magnetic Amplifier

The high gain of the amplifiers can be achieved with a new amorphous metal core and a careful winding technique.

The characteristic of the core is shown in figure 5.

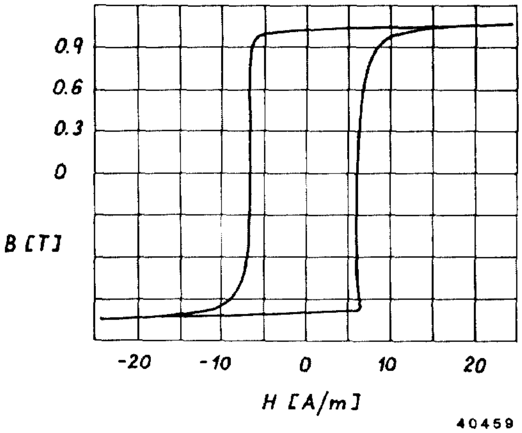

Fig. 5: Hysteresis of the core material

As was pointed out, the energy stored in a quenching magnet has to be absorbed in that magnet. This can cause problems for the main dipole magnets which store up to 1.37 MJ. If the quench starts at a low field point in the magnet, the development of the normal conducting region might be too slow to keep the density of absorbed energy everywhere low enough to avoid local overheating. The dipoles are, therefore, equipped with two heater bands, which are independently connected to capacitors banks charged to 730 J for each heater band. The capacitors are placed in the nearest hall, which makes the maintenance easier, eases automatic tests to be performed by microprocessors, and allows the use of lower cost capacitors. Tests with spot heater induced quenches confirmed, that under realistic assumptions about the cause of a quench, one heater band should be sufficient. Nevertheless, to be safe against the malfunction of a heater, both heater bands are connected. Furthermore, for beam induced quenches heater tapes may even not be necessary.

Figure 6 summarizes the active part of the quench protection system.

Dipole quenches are detected either by individual magnetic amplifiers, which directly fire the corresponding heaters, or, as a backup, by a group detection system. In the latter case a microprocessor commands the heater firing. For the quadrupoles and correction elements a similar system is used, except that no heaters have to be fired. The microprocessors continuously conduct tests on the availability of (almost) all components and connections. Malfunctions are reported immediately, and appropriate action is taken. The switches are activated by a special direct line.

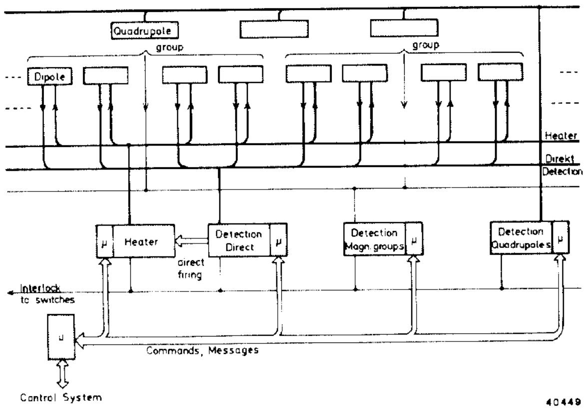

Fig. 6: Quenchprotection at HERA

Conclusions

The HERA quench protection system is based on cold diodes to keep quenching magnets safe from the stored energy of all other magnets, and on a subdivision of the electrical circuit to limit the voltages. Quenches are detected by magnetic amplifiers which sense the current in the center connection of a bridge. The corresponding electronics is located in the nearest hall (up to 1 km away). Heaters are fired either directly, or, in case of malfunction, via the backup detection system on command of a microprocessor. Almost all components can be tested even with beam in the storage ring.

References

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